

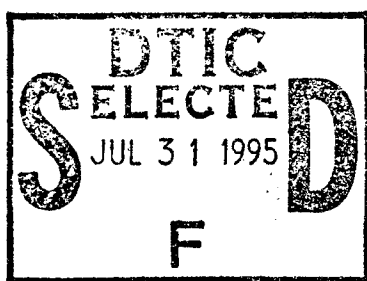
RL-TR-95-91
Final Technical Report
May 1995



NOVEL OPTICAL FIBERS AND DEVICES

Brown University

T.F. Morse



APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

19950728 035

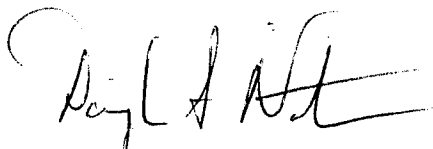
DTIC QUALITY INSPECTED 5

Rome Laboratory
Air Force Materiel Command
Griffiss Air Force Base, New York

This report has been reviewed by the Rome Laboratory Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

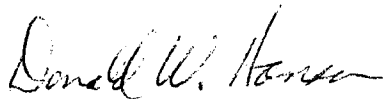
RL-TR-95-91 has been reviewed and is approved for publication.

APPROVED:



DOUGLAS A. NORTON
Project Engineer

FOR THE COMMANDER:



DONALD W. HANSON
Director of Surveillance & Photonics

If your address has changed or if you wish to be removed from the Rome Laboratory mailing list, or if the addressee is no longer employed by your organization, please notify RL (OCPA) Griffiss AFB NY 13441. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document require that it be returned.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave Blank)		2. REPORT DATE May 1995		3. REPORT TYPE AND DATES COVERED Final May 94 - Dec 94	
4. TITLE AND SUBTITLE NOVEL OPTICAL FIBERS AND DEVICES				5. FUNDING NUMBERS C - F30602-94-C-0079 PE - 62702F PR - 4600 TA - P4 WU - PC	
6. AUTHOR(S) T.F. Morse					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Brown University Division of Engineering Providence RI 02912				8. PERFORMING ORGANIZATION REPORT NUMBER N/A	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Rome Laboratory (OCPA) 25 Electronic Pky Griffiss AFB NY 13441-4515				10. SPONSORING/MONITORING AGENCY REPORT NUMBER RL-TR-95-91	
11. SUPPLEMENTARY NOTES Rome Laboratory Project Engineer: Douglas A. Norton/OCPA/(315) 330-2944					
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.				12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Investigation into the design and fabrication of high dispersion optical fiber is presented. Once fabricated, this high dispersion fiber could be used in signal processing and communications systems. A novel optical switch that is fabricated using highly over-coupled couplers (HOCC) is also presented. By changing the length of the fused taper section of 2x2 coupled fiber, the ratio of the power of the two outputs will change. This device can also be used for strain measurement as well as for modulation.					
14. SUBJECT TERMS Fiber optics, Pulse compression, Optical switches				15. NUMBER OF PAGES 20	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL		

I. Research Accomplishments in 1994

The major research accomplishment during the past year was the development of highly overcoupled couplers (HOCC) that can be used as switches [1], and in the demodulation of Bragg gratings. We are able to illustrate an improved technique capable of detecting small Bragg wavelength shifts using highly over coupled couplers (HOCC). The light intensity in an output arm changes by 60% with each nanometer change in the peak Bragg wavelength. This was achieved with an HOCC fabricated with 600 cycles. The minimum detectability is six times smaller than previously reported using a commercial wavelength division multiplexer (WDM) (10%/nm). With our HOCC, a 5 μ W LED and a 95% reflective Bragg grating we could detect 10 μ strain. This compares favorably with an optical spectrum analyzer which has a typical resolution of 0.1 nm (corresponding to 100 μ strain under the same experimental conditions). This is an inexpensive technique for measuring wavelength shifts.

II. HOCCs as Bragg Grating Demodulators

Fiber Bragg gratings (FBG) are made by producing a periodic perturbation in the index of reflection of the fiber core, and these structures are useful in techniques involving both active and passive fiber devices [2]. The advantages of these gratings are that they are compatible with fiber network systems, they have low insertion loss and can be used as narrow band reflectors in all optical fiber lasers and as strain or temperature sensing devices. In contrast, an expensive spectrum analyzer with maximum resolution of 0.1 nm is usually used to detect Bragg wavelength shifts in sensing applications.

Recently, much effort has been focused on developing simple and inexpensive techniques to detect Bragg wavelength shifts [3-5]. These shifts can be measured using interferometric schemes [3] or using the slope of a broad band filter [4]. Davis and Kersey [3] reported that a commercially available wavelength division multiplexer (WDM) can be used for wavelength shift detection since it exhibits a characteristic wavelength to intensity transfer function which is referred to as the spectral slope. The spectral slope of a commercial WDM is, typically, less than 10%/nm and this limits the minimum detectable Bragg wavelength shift. One can use a very powerful light source to compensate for the limitations due to a shallow slope function. In this paper, we present an improvement that uses highly over-coupled couplers (HOCC) to improve the slope steepness. We have fabricated these devices in our laboratory for use as optical switches, narrowband WDM, sensors, and Bragg grating demodulators [6,7]. As a result, even with a weak light source, we are able to detect 10 μ strain.

The spectral slope of a coupler is determined by the pulling length during the

coupler fabrication process [8]. The coupling phenomenon is caused by the mode beating [8] that takes place in the narrow fiber neck section. As the fibers are fused together in this neck section the extent of mode beating is a function of the optical path length along this core. During the coupler fabrication process, the output intensities are measured from the two leads of the coupler. 1 shows a typical measured intensity cycling of a HOCC fabricated using a 1300 nm laser diode as light source. It can be shown that the number of cycles increases exponentially with the elongation length.

Commercial 3dB couplers are usually made by stopping the elongation and consequently the coupling process after the first cycle. These devices have a dependence of (intensity shift)/ $(\Delta\lambda)_{Bragg} \approx (0.2\%/nm)$. A WDM can be made utilizing Over Coupled Couplers (OCC) by controlling the number of cycles to produce the desired spectral response. Typically, fiber coupler WDM's are made by elongating the fibers such that several cycles occur. Therefore, a WDM is a slightly over-coupled coupler. Using an arbitrary measure, we define couplers with over 100 cycles as highly over-coupled couplers (HOCC). Their properties are discussed below.

The minimum detectable Bragg wavelength shift that may be detected using a HOCC may be estimated as follows. From Fig. 2, we see that as the number of cycles increases, the bandwidth (BW=distance between cycles) decreases such that $N \times BW = \text{const}$. We may approximate the slope of the intensity as a function of wavelength such that (slope) $\approx I/(BW/4)$. See Fig. 2. Therefore, if a signal sent through the coupler changes by $\Delta\lambda$, there will be a corresponding change in the detected intensity. This is given as

$$\frac{(\Delta I)_{detected}}{(\Delta\lambda)_{Braggshift}} = 4I/BW$$

Since $\frac{\Delta\lambda}{\lambda} = .78 \frac{\Delta L}{L}$, where $\frac{\Delta L}{L}$ is the strain, we obtain the result that

$$\frac{\Delta L}{L} \approx \frac{\Delta I}{I} \frac{1}{4N\lambda}$$

The above expression assumes that the coupler is lossless, and that increasing N always leads to increased sensitivity. As seen in Fig. 1, for an HOCC, the intensity can decrease and the coupler in the final stage, cycles between 30% and 70%. This does not necessarily indicate an inefficient coupler. The explanation for this phenomenon is that the mode beating that determines the coupler cycling depends upon a beating between the fundamental symmetric mode and the first order anti-symmetric mode. If both modes share the same fraction of power, the beating magnitude is 100%. However when mode conversion occurs, a fraction of the power in the antisymmetric mode is transferred to the fundamental mode

resulting in incomplete transfer of power between the fibers. This is analogous to the decrease in fringe visibility that can occur in interferometry. We have observed at approximately 2000 cycles, when the modal cutoff is approached [7], the fibers become too small to support the propagation of the antisymmetric mode. The oscillation behavior completely vanishes resulting in a zero slope.

Therefore, while it is advantageous to increase the slope by using HOCCs, the maximum wavelength shift that can be detected in the "linear" portion of a cycle becomes smaller as N increases. This can be seen in Fig. 2, where we show first a significant increase in sensitivity with increasing number of cycles, a peak near 650 cycles, and then a decline. Thus, for the HOCC's fabricated for this work, there appears to be a maximum in the sensitivity that can be obtained. The value of $NBW = \text{const.}$ is obtained from Fig.2, and the constant has the numerical value of xxxx. Using the $N=650$ as the optimum number of cycles, we find that

$$\frac{\Delta L}{L} = 4.36 \times 10^{-4} \frac{\Delta I}{I}$$

Our detector was such that $\frac{\Delta I}{I} \approx .02$, and a minimum detectable Bragg shift of 10μ strains is obtained. With better detector stability this can be readily improved upon.

With $\Delta\lambda/\lambda = 0.78 \Delta l/l$, a strain application at a wavelength of 1550 nm will require the detection of a maximum wavelength shift of 12 nm. In such a case, a HOCC must be made with approximately 50 cycles for the maximum slope to correspond to the maximum change. The spectral response of an HOCC with 626 cycles is shown in Fig. 2. The maximum wavelength change that this can demodulate in the linear range is 2.6 nm, which corresponds to a total strain of 2200 μ -strain. This is well within the limit to which a fiber can be strained, typically $\approx 1\%$.

In order to tune the HOCC to the desired spectral position, a temperature controlled package was developed. This also reduced thermal fluctuations. As shown in Fig. 3, the spectrum of the HOCC shifts towards shorter wavelengths as ambient temperature increases. In the present study, the Bragg wavelength was centered at 1548.3 nm. The ambient temperature was elevated to 45 °C in order to position the spectrum at the desired linear region.

Fig. 4 shows the experimental setup for measuring Bragg wavelength shifts using an HOCC with a 5 μ W edge emitting LED at 1550 nm as the light source. The 95% reflective grating was fabricated in a hydrogen loaded AT&T Accutether fiber. The fiber was then exposed to KrF excimer laser for 60 seconds. A 1070 nm phase mask was used to generate the interference pattern. The grating fiber was fusion spliced to a regular 3 dB coupler at 1550 nm. On the receiving port, one arm

of the 3 dB coupler was also fusion spliced to the 626 cycle HOCC. The outputs from the HOCC were received by a pair of germanium photodiodes and processed by computer software as shown in Fig. 4 to eliminate the power fluctuations from the light source.

The fiber on either side of the Bragg grating sensor was bonded to a micro-translational stage to provide accurate displacement measurements. Strain was calculated by division of the displacement value over the total fiber length between the two bonding points. Fig. 5 shows the sensor output measured as a function of strain. As can be seen excellent linearity was observed throughout the measured region. In addition, the system showed good long term stability and repeatability. The data in Fig. 5 indicate a minimum strain detectability of 10 micro strain, when an LED emitting 5 μ W of power was used. This is an improvement of at least 2 orders of magnitude compared with previously reported results using a WDM. The improvement is due to the increase in the spectral slope of the HOCC used to detect the Bragg wavelength shifts.

Since the spectral slope of an HOCC is directly proportional to the intensity of light launched into the fiber, using a stronger light source will significantly increase the minimum detectability, ie., the smallest $\Delta(\lambda)$ in the Bragg wavelength peak. The HOCC presented here has a spectral range of 2.1 nm corresponding to a maximum wavelength shift of 1 millistrain. Since an HOCC can be fabricated with a specific number of cycles (up to the modal cut-off), the number of cycles can be based on the desired sensitivity and dynamic range. See Fig. 2.

In conclusion, we have demonstrated an improved technique to detect the Bragg wavelength shifts by using HOCCs. For the HOCC used here, It was found that the spectral slope increases initially with the cycles and reaches the maximum value at approximately 600 cycles. This will vary for different HOCC's. The minimum detectability of approximately 10 micro strain was achieved when a 5 μ W LED and a 626 cycles HOCC were used. Since the sensitivity (minimum detectable Bragg wavelength shift) is proportional to the strength of the light source, a 500 μ W LED would permit the measurement of .1 μ strain.

III. Dispersion Shifted Fibers

The other task that we had addressed during this past year was that of obtaining a fiber with high dispersion so that pulse spreading can be compensated. Initially, we had envisioned that a Ta doped optical fiber would have more material dispersion than a Ge doped fiber. This proved not to be the case and the Ta doped fiber that we produced that was evaluated at the Photonics Laboratory proved to have minimal dispersion. Upon further discussion with Dr. Ann Miller of AT&T, we obtained fiber profiles and doping levels that have produced high dispersion with relatively

low loss. It will be our intention during the coming months to fabricate some of these profiles that will have higher values of dispersion, and that can be used to compensate for pulse spreading.

IV. Future Efforts

Future efforts will concentrate on development of the electro-optic switch described above. We will also place particular effort on the fabrication of optical fibers that may be used for dispersion compensation. In addition, we will attempt to use our Bragg grating technology to fabricate MOPA's (Master Oscillator Power Amplifiers) in the 2.0 micron region.

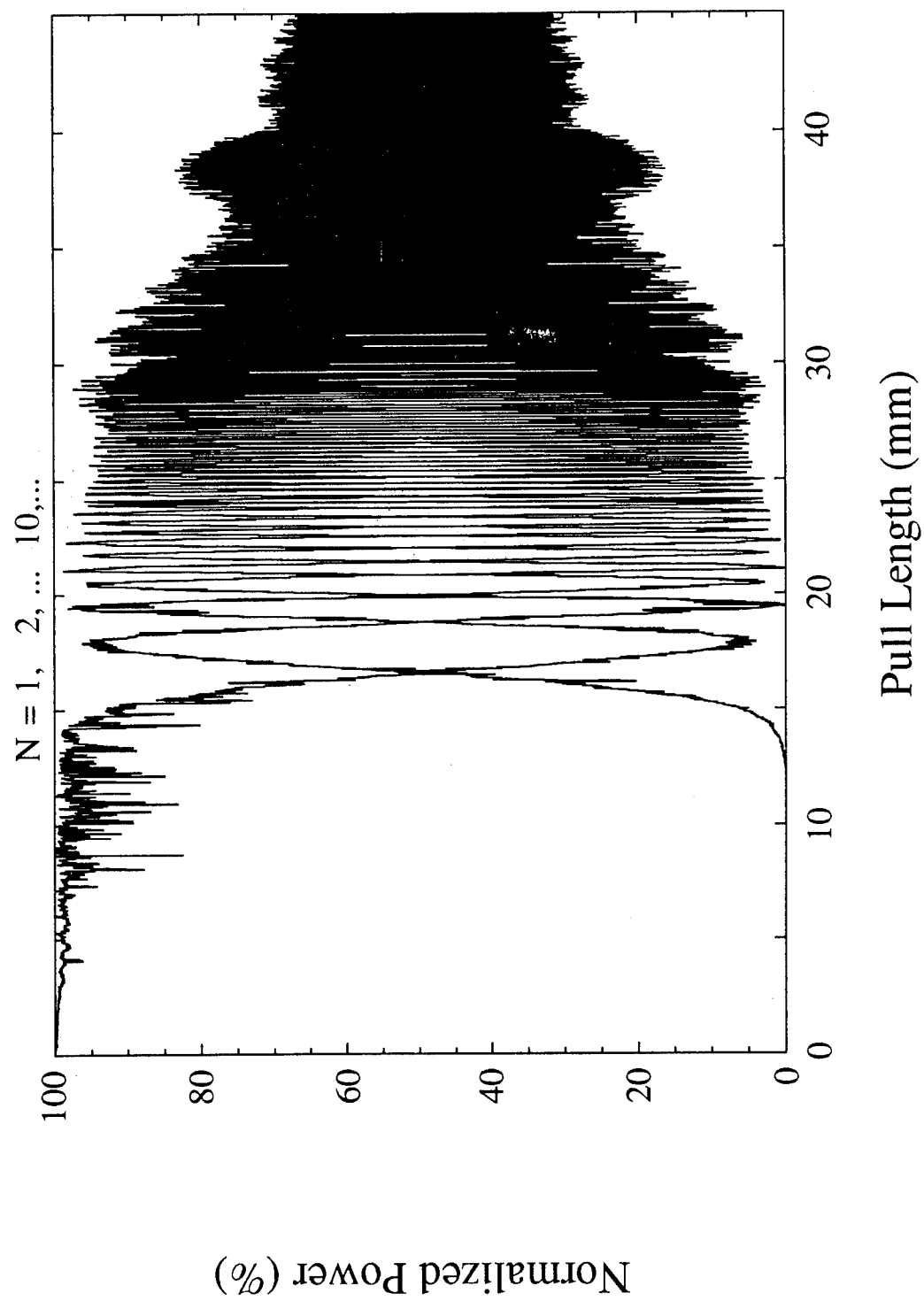
V. Figure captions:

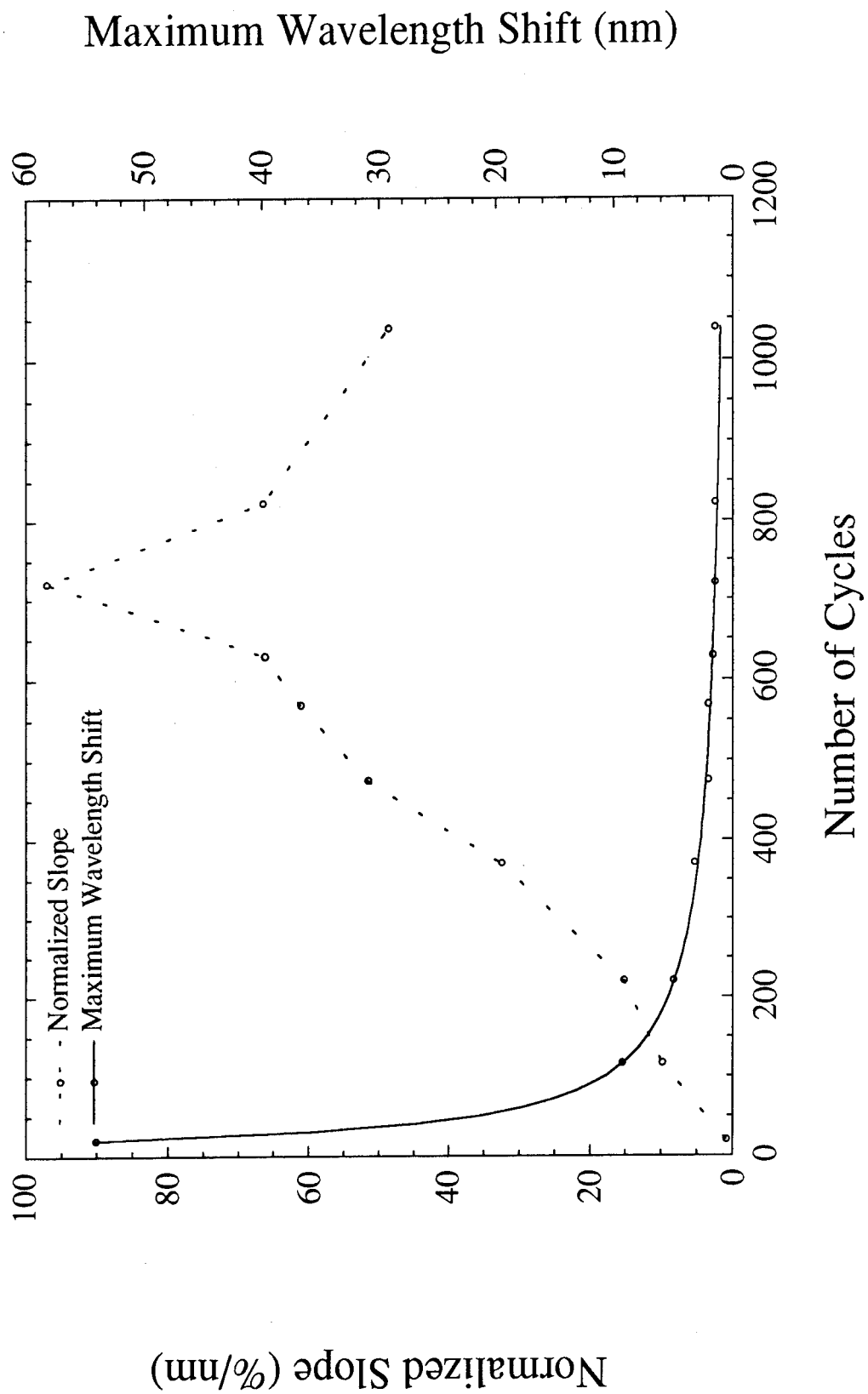
- Fig. 1. The normalized output from the two fiber leads of a HOCC taken during the manufacturing process.
- Fig. 2. Maximum wavelength shift as a function of the number of cycles; Normalized slope $(\Delta(I)/I)/\Delta(\lambda)/\lambda$
- Fig. 3. Spectral response of 626 cycle HOCC. Dashed line: room temperature; solid line: 45 °C.
- Fig. 4. Experimental setup for Bragg wavelength detection using HOCC.
- Fig. 5. Experimental measurements from the sensor indicates good linear response.

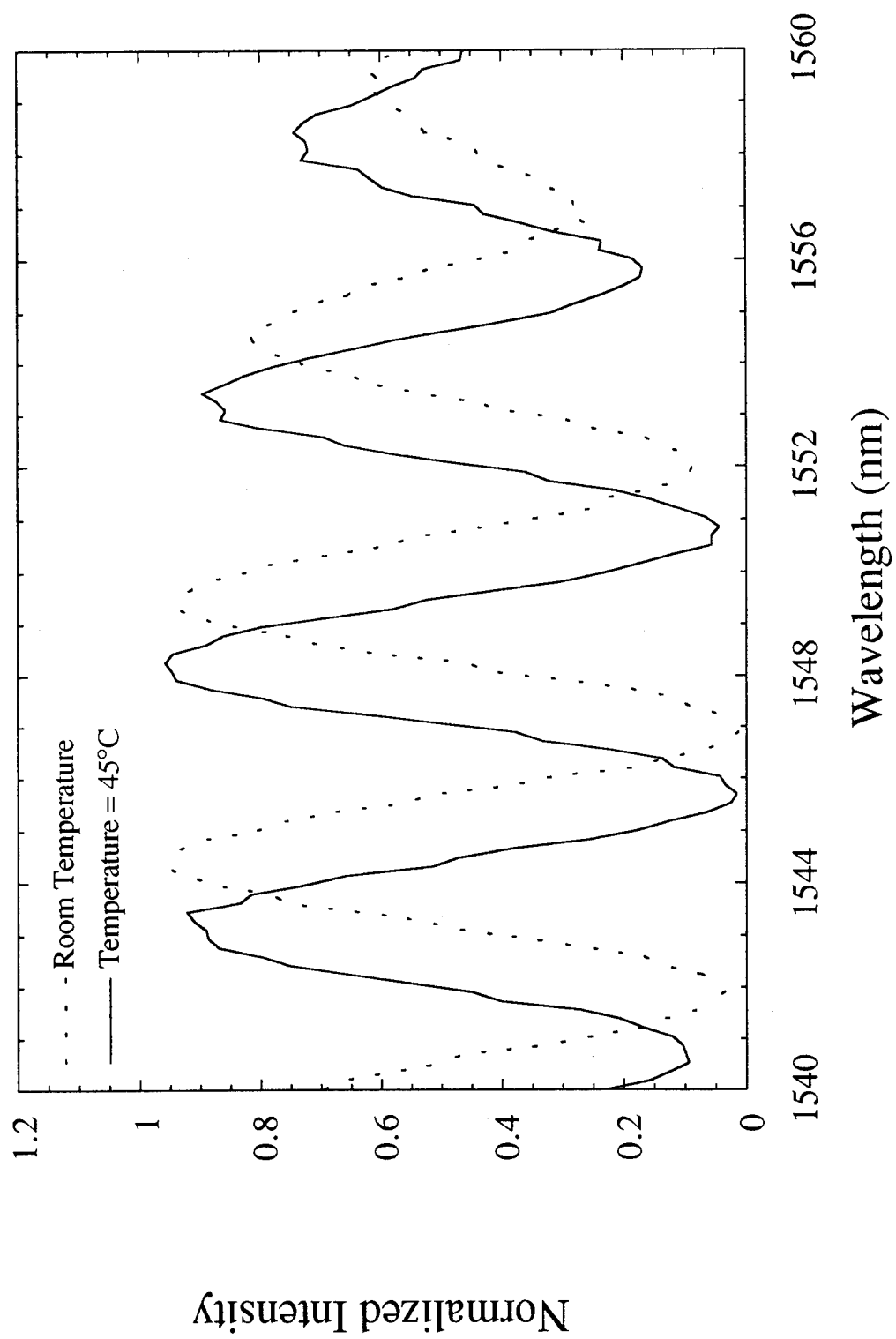
VI. References

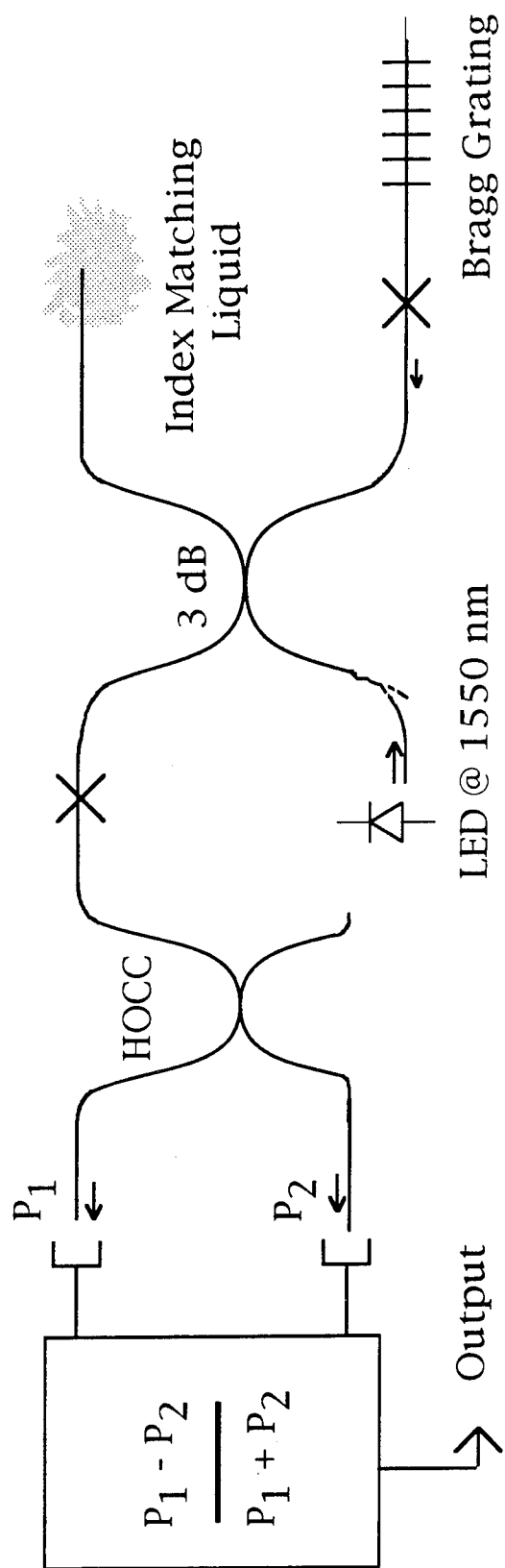
1. Morse, T.F., Chen, Meng-Pan, Reinhart, L. and Brown, D.R. "Highly Over-coupled Fused Taper Couplers as Optical Switches" SPIE publication, 1994.
2. Meltz, G., Morey, W.W., and Glenn, W.H., "Formation of Bragg gratings in optical fiber by a transverse holographic method", *Opt. Lett.*, 1989, **14**, pp. 823-5.
3. Davis, M.A., and Kersey, A.D., "All-fibre Bragg grating strain-sensor demodulation technique using a wavelength division coupler", *Electron. Lett.*, 1994, **30**, pp. 75-77.
4. Kersey, A.D., Berkoff, T.A., and Morey, W.W., "High resolution fibre grating based strain sensor with interferometric wavelength shift detection", *Electron. Lett.*, 1992, **28**, p. 236.

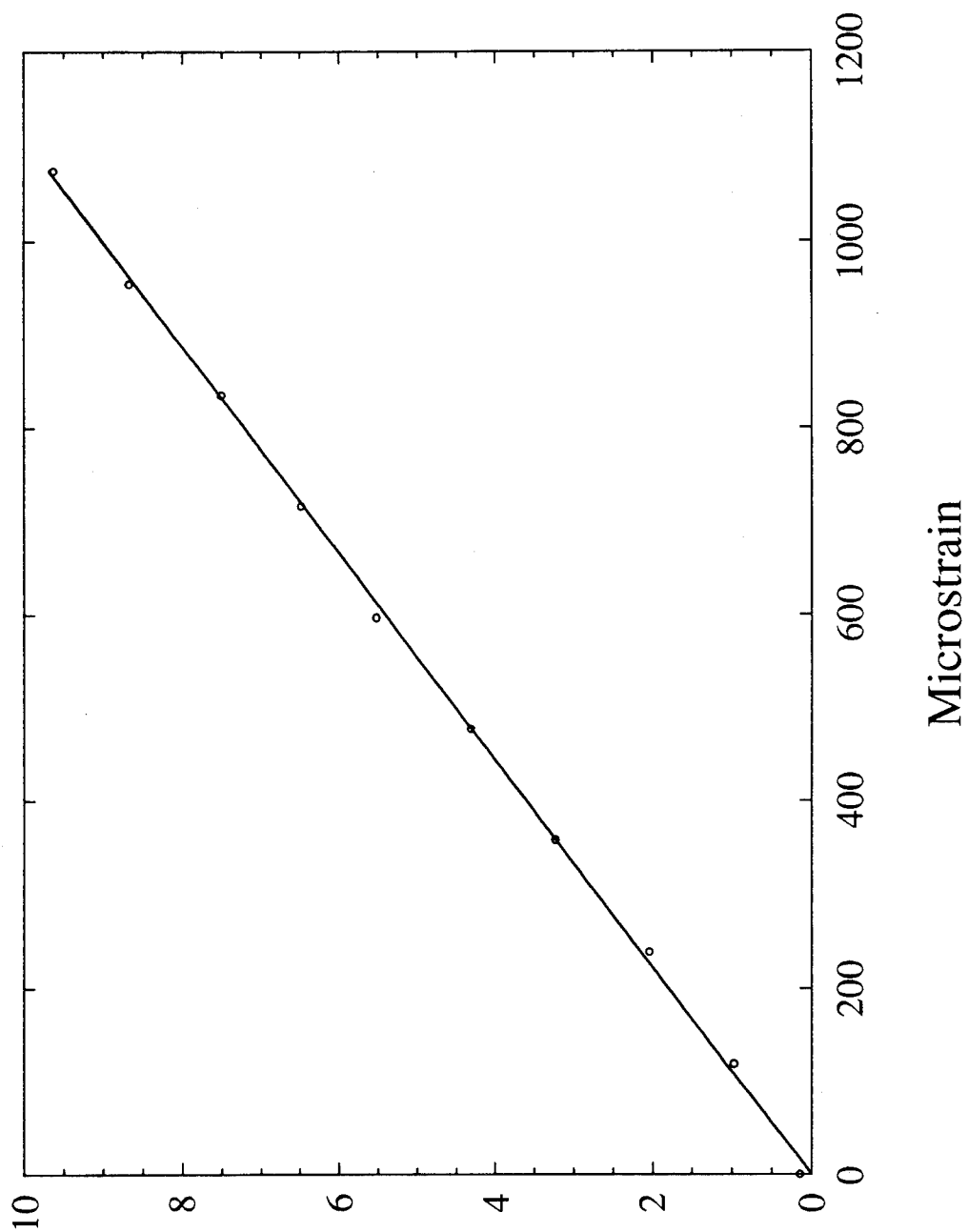
5. Kersey, A.D., "Interrogation multiplexing techniques for fiber Bragg grating strain sensors", Proc. SPIE, 1993.
6. Morse, T.F., Chen, M.P., Reinhart, L., and Brown, D.A., "Highly overcoupled fused taper couplers as optical switches", Proc. SPIE, vol. 2216, 1994, pp. 210-222.
7. Mengpang Chen, Ph. D. thesis, Aug. 1994, Brown University.
8. Bilodeau, F., Hill, K.O., Johnson, D.C., and Faucher, S., "Compact, low-loss, fused biconical taper couplers: overcoupled operation and antisymmetric supermode cutoff", *Opt. Lett.*, 1987, pp. 634-6.
9. Bures, J., Lacroix, S., and Lapierre, J., "Analyse d'un coupleur bidirectionnel à fibres optiques monomodes fusionnées", *Appl. Opt.*, 1983, pp. 1918-21.











Sensor Output (arbitrary units)

U.S. GOVERNMENT PRINTING OFFICE: 1995-610-126-50248

Rome Laboratory
Customer Satisfaction Survey

RL-TR-_____

Please complete this survey, and mail to RL/IMPS,
26 Electronic Pky, Griffiss AFB NY 13441-4514. Your assessment and
feedback regarding this technical report will allow Rome Laboratory
to have a vehicle to continuously improve our methods of research,
publication, and customer satisfaction. Your assistance is greatly
appreciated.
Thank You

Organization Name: _____(Optional)

Organization POC: _____(Optional)

Address: _____

1. On a scale of 1 to 5 how would you rate the technology
developed under this research?

5-Extremely Useful 1-Not Useful/Wasteful

Rating_____

Please use the space below to comment on your rating. Please
suggest improvements. Use the back of this sheet if necessary.

2. Do any specific areas of the report stand out as exceptional?

Yes____ No_____

If yes, please identify the area(s), and comment on what
aspects make them "stand out."

3. Do any specific areas of the report stand out as inferior?

Yes___ No___

If yes, please identify the area(s), and comment on what aspects make them "stand out."

4. Please utilize the space below to comment on any other aspects of the report. Comments on both technical content and reporting format are desired.

***MISSION
OF
ROME LABORATORY***

Mission. The mission of Rome Laboratory is to advance the science and technologies of command, control, communications and intelligence and to transition them into systems to meet customer needs. To achieve this, Rome Lab:

- a. Conducts vigorous research, development and test programs in all applicable technologies;
- b. Transitions technology to current and future systems to improve operational capability, readiness, and supportability;
- c. Provides a full range of technical support to Air Force Materiel Command product centers and other Air Force organizations;
- d. Promotes transfer of technology to the private sector;
- e. Maintains leading edge technological expertise in the areas of surveillance, communications, command and control, intelligence, reliability science, electro-magnetic technology, photonics, signal processing, and computational science.

The thrust areas of technical competence include: Surveillance, Communications, Command and Control, Intelligence, Signal Processing, Computer Science and Technology, Electromagnetic Technology, Photonics and Reliability Sciences.